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The formation of brown dwarfs

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Abstract. We review four mechanisms for forming brown dwarfs: (i) turbulent fragmentation (producing very low-mass prestellar cores); (ii) gravitational instabilities in discs; (iii) dynamical ejection of stellar embryos from their placental cores; and (iv) photo-erosion of pre-existing cores in HII regions. We argue (a) that these are simply the mechanisms of *low-mass star formation*, and (b) that they are not mutually exclusive. If, as seems possible, all four mechanisms operate in nature, their relative importance may eventually be constrained by their ability to reproduce the binary statistics of brown dwarfs, but this will require fully 3-D radiative magneto-hydrodynamic simulations.

Key words: Star formation - brown dwarfs

1. Introduction

The existence of brown dwarfs was first proposed on theoretical grounds by Kumar (1963) and by Hayashi & Nakano (1963). However, more than three decades then passed before brown dwarfs were observed unambiguously (Rebolo et al., 1995; Nakajima et al., 1995; Oppenheimer et al. 1995). Brown dwarfs are now observed routinely, and are estimated to be comparable in number with hydrogen-burning stars. It is therefore appropriate to ask how brown dwarfs form, and in particular to ascertain (a) whether brown dwarfs form in the same way as hydrogen-burning stars, and (b) whether there is a clear distinction between the mechanisms that produce brown dwarfs and those that produce planets.

In Section 2 we argue that brown dwarfs do form in the same way as stars, on the grounds that their statistical properties (mass function, binary statistics, clustering properties, etc.) appear to form a smooth continuum with those of low-mass hydrogen-burning stars. We also suggest that understanding how brown dwarfs form is the key to answering a fundamental anthropic question, namely, what determines the lower mass limit for star formation, and thereby the likelihood of long-lived stars with habitable zones. In Section 3 we consider the formation of brown dwarfs by turbulent fragmentation, as suggested by Padoan & Nordlund (2002), and we address the question of whether an isolated core of brown-dwarf mass formed in this way can cool sufficiently fast to condense out. In Section 4 we consider the formation of brown dwarfs by gravitational instabilities in discs. We stress that only in massive discs, and at large radii, can fragments of a disc contract and cool sufficiently fast to condense out; closer in they are likely to bounce and be shredded. We also point out that, in a dense proto-cluster, impulsive interactions between discs, or between a disc and a naked star, should be common, and may be necessary to ensure disc fragmentation. In Section 5 we consider the formation of brown dwarfs by the ejection mechanism, as suggested by Reipurth & Clarke (2001). We point out that the requirements for this mechanism to operate are very general, and therefore it is likely to occur in nature, although it is probably not the only mechanism forming brown dwarfs, given the difficulty it has producing close BD-BD binaries. In Section 6 we consider the formation of brown dwarfs by photo-erosion of pre-existing cores which are overrun by HII regions, as suggested by Hester et al. (1996). We stress that this a very robust mechanism, in the sense that it does not require very fine tuning of the parameters; but it is also a very inefficient mechanism, in the sense that it requires a very massive inital core to form a brown-dwarf, and it clearly cannot deliver the brown dwarfs in regions like Taurus. In Section 7 we summarise our review.

2. Why brown dwarfs appear to form like H-burning stars

We shall assume that brown dwarfs form in the same way as hydrogen-burning stars, i.e. on a dynamical timescale, by gravitational instability, and with initially uniform elemental

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composition (reflecting the elemental composition of the interstellar medium out of which they form). Thus, by implication, we distinguish brown dwarfs from planets, which form on a much longer timescale, by the amalgamation of a rocky core and – if circumstances allow – the subsequent accretion of a gaseous enevelope, resulting in an initially fractionated elemental composition with an overall deficit of volatile/light elements. If this is the correct way to view the formation of brown dwarfs, and we argue below that it is, then brown dwarfs should not be distinguished from stars; many stars fail to burn helium, and most fail to burn carbon, without forfeiting the right to be called stars.

The reason for categorising brown dwarfs as stars is that the statistical properties of brown dwarfs appear to form a continuum with those of low-mass hydrogen-burning stars.

(i) IMF. The initial mass function is apparently continuous across the hydrogen-burning limit at $\sim 0.075\,\mathrm{M_\odot}$. This is not surprising, since the processes which determine the mass of a star are presumed to occur at relatively low densities and temperatures, long before the protostellar material knows whether it will reach sufficiently high temperature to burn hydrogen before or after reaching sufficiently high density to be supported in perpetuity by electron degeneracy pressure. In the light of this continuity, it seems perverse to have to speak of 'The IMF for Stars and Brown Dwarfs' when 'The Stellar IMF' is already quite long enough.

(ii) Clustering properties. In clusters, brown dwarfs appear to be homogeneously mixed with H-burning stars, and their kinematics are also essentially indistinguishable. Although they have been searched for – as possible signatures of formation by ejection – neither a greater velocity dispersion of brown dwarfs in very young clusters, nor a diaspora of brown dwarfs around older clusters, has been found.

(iii) Binary statistics. Here we have to distinguish at least two types of binary system.

In the first type of binary system, the primary is a Sun-like star and the secondary component is a brown dwarf. Amongst this type there is a remarkable lack of close systems (the Brown Dwarf Desert). However, at larger separations (semi-major axis $a \gtrsim 100\,\mathrm{AU}$), brown-dwarf secondaries are quite common. Moreover, the lack of close low-mass secondaries is not confined to brown dwarfs. There appears to be a general lack of systems with very low mass-ratios, $q \lesssim 0.1$.

In the second type of binary system, the primary is a brown dwarf, and therefore the secondary is also a brown dwarf (or possibly even a planetary-mass object, if this distinction must be made, see below). For brown-dwarf primaries, the multiplicity is estimated to be $m \sim 30\,\mathrm{to}\,40\,\%$, the distribution of semi-major axes peaks at $a_{\mathrm{PEAK}} \sim 4\,\mathrm{AU}$ with a logarithmic dispersion $\sigma_{\log 10\,a} \sim 0.6$, and the mean mass-ratio is $\bar{q} \sim 0.7$. In comparison, G-dwarf primaries are estimated to have $m \sim 60\,\%$, $a_{\mathrm{PEAK}} \sim 30\,\mathrm{AU}$, $\sigma_{\log 10\,a} \sim 1.6$, and $\bar{q} \sim 0.3$. The implication is that, as the primary mass decreases, (i) the multiplicity decreases (but only quite slowly), (ii) the distribution of semi-major axes shifts to smaller separations and becomes narrower (logarithmically), and (iii) the distribution of mass ratios shifts towards unity – with these trends continuing across the divide between brown dwarfs and H-burning stars.

In fact, the situation is even more complicated than this, since there are several systems in which (a) the primary is a close binary with Sun-like components (rather than a single Sun-like star), and/or (b) the Sun-like primary is orbited at large radius ($\gtrsim 100\,\mathrm{AU}$) by a close BD-BD binary. However, the statistics of these systems are limited.

(iv) Discs, accretion and outflows. Young brown dwarfs are observed to have infrared excesses indicative of circumstellar discs, just like young H-burning stars. From their Hα emission-line profiles, there is also evidence for ongoing accretion onto brown dwarfs, and the inferred accretion rates form a continuous distribution with those for H-burning stars, fitted approximately by $\dot{M} \sim 10^{-8}\,\mathrm{M_\odot\,yr^{-1}}\,\left(M/\mathrm{M_\odot}\right)^2$. Finally, the spectra of brown dwarfs also show forbidden emission lines suggestive of outflows like those from H-burning stars, and recently an outflow from a brown dwarf has been resolved spatially. Thus, in the details of their circumstellar discs, accretion rates and outflows, young brown dwarfs appear to mimic H-burning stars very closely, and to differ significantly only in scale.

Given this continuity of statistical properties between brown dwarfs and H-burning stars, it is probably unhelpful to distinguish brown dwarfs from stars, and in the rest of the paper we will only use the H-burning limit at $\sim 0.075\mathrm{M_\odot}$ as one of several reference points in the range of stellar masses. The D-burning limit at $\sim\,0.013\,\mathrm{M_\odot}$ therefore falls in the same category. We will then define a star as any object forming on a dynamical timescale, by gravitational instability, and therefore with uniform interstellar elemental composition. With this definition, there is the distinct likelihood of a small overlap between the mass range of stars and that of planets. Given that in the immediate future we are unlikely to know too much more than the masses of the lowest-mass objects, and certainly not their internal composition, we will simply have to accept that there is a grey area in the range $0.001\,\mathrm{to}\,0.01\,\mathrm{M_\odot}$ which may harbour both stars and planets.

It follows that understanding how brown dwarfs form is important, not just for its own sake, but because it is the same as understanding how very low-mass stars form. Thus brown dwarf formation is a key part of understanding why most stars have masses in the range $0.01\,\mathrm{M_\odot}$ to $100\,\mathrm{M_\odot}$, and hence why there are lots of hospitable stars like the Sun with long-lived habitable zones, and enough heavy elements (C, N, O, Si, Mg, Al, Fe, etc.) to produce rocky planets and life. The high-mass cut-off is probably due to the fact that radiation pressure makes it hard to form the highest-mass stars; and the low-mass cut-off is probably due to the opacity limit. By studying brown dwarf formation we can attempt to confirm and quantify the low-mass cut-off.

3. Formation by turbulent fragmentation

The first possibility that we consider is that the processes forming prestellar cores create some prestellar cores with very low masses. Very low-mass cores must inevitably spawn

very low-mass stars, even if they don't fragment during collapse. This is the formation mechanism that has been explored by Padoan & Nordlund (2002). By simulating the development of interstellar turbulence, they show that a wide range of dense structures is formed. If those structures which are dense and coherent enough to be gravitationally unstable are identified as prestellar cores, they have a mass spectrum very similar to the observed stellar IMF. There is support for this scheme from the observations of Motte, André & Neri (1998) who show that the mass function for cores does indeed appear to echo the stellar IMF. However, we note (i) that the core mass function should relate more closely to the system IMF (rather than the stellar IMF), and (ii) that the completeness limit of the core mass function does not extend to brown-dwarf masses. Moreover, the simulations of Padoan & Nordlund do not include gravity, and they use an isothermal equation of state. Therefore they do not address the requirement that dynamically contracting cores must be able to radiate away at least half the gravitational potential energy being released by condensation.

This requirement is normally referred to as the Opacity Limit (but see Masunaga & Inutsuka, 1999), and is presumed to determine the minimum mass for star formation. Traditionally, the Opacity Limit has been evaluated on the basis of the 3-D hierarchical fragmentation picture developed by Hoyle (1953). In this picture, a large protocluster cloud becomes Jeans unstable and starts to contract. As long as the sound speed in the gas remains approximately constant, the increasing density reduces the Jeans mass, and so separate parts of the cloud (sub-clouds) become Jeans unstable and can contract independently of one another. This process repeats itself recursively, breaking the original cloud up into ever smaller and denser sub-sub...sub-clouds, until the gas becomes so opaque that it can no longer radiate away the gravitational energy being released by contraction. At this stage the gas starts to heat up, and fragmentation ceases. This yields a minimum mass in the range $M_{\rm MIN} \sim 0.007\,{\rm M}_{\odot}$ to $0.015\,{\rm M}_{\odot}$ (e.g. Low & Lynden-Bell, 1976; Rees, 1976; Silk, 1977).

However, it appears that 3-D hierarchical fragmentation does not work. There is no evidence for its occuring in nature, nor does it occur in numerical simulations of star formation. The reason 3-D hierarchical fragmentation does not work probably has to do with the fact that the timescale on which a fragment condenses out in 3-D is always longer than the timescale on which the parent cloud is contracting. Therefore fragmentation, if it occurs at all, is only temporary, and the fragments are then merged by the overall contraction of the parent cloud. The only way to avoid this is to start with fragments which are widely spaced, but then the rate of accretion onto a fragment is very high, and even if it starts off with mass $M_{\rm FRAG} \sim M_{\rm JEANS}$, it will be many times more massive by the time its contraction becomes non-linear. Thus the values for $M_{\rm MIN}$ quoted in the previous paragraph are probably significant underestimates for hierarchical 3-D fragmentation.

It is therefore appropriate to revisit the question of the minimum mass for fragmentation, but now using a model which invokes 2-D one-shot fragmentation of a shock-compressed layer. We argue that this model is more relevant to the contemporary scenario of 'star formation in a crossing time' (Elmegreen, 2000), and in particular to the scenario simulated by Padoan & Nordlund (2002). In this scenario star formation occurs in molecular clouds wherever two – or more – turbulent flows of sufficient density collide with sufficient ram pressure to produce a shock-compressed layer out of which prestellar cores can condense. The model is '2-D' because fragmentation of a shock-compressed layer is in effect two-dimensional (the motions which initially assemble a fragment are largely in the plane of the layer), and it is 'one-shot' in the sense of not being hierarchical or recursive.

A shock-compressed layer is contained by the ram pressure of the inflowing gas, and until it fragments it has a rather flat density profile. If we consider the simplest case of a head-on collision between two streams of equal density, the resulting layer fragments at time $t_{\rm FRAG}$, whilst it is still accumulating, and the fastest growing fragment has mass $m_{\rm FRAG}$, radius $r_{\rm FRAG}$ (in the plane of the layer) and half-thickness $z_{\rm FRAG}$ (perpendicular to the plane of the layer) given by

$$t_{\rm FRAG} \sim (\sigma/G\rho v)^{1/2}\,, \tag{1}$$
$$m_{\rm FRAG} \sim (\sigma^7/G^3\rho v)^{1/2}\,, \tag{2}$$
$$r_{\rm FRAG} \sim (\sigma^3/G\rho v)^{1/2}\,, \tag{3}$$
$$z_{\rm FRAG} \sim (\sigma^5/G\rho v^3)^{1/2}\,. \tag{4}$$

Here σ is the net velocity dispersion in the layer, ρ is the pre-shock density in the colliding flows, and v is the relative speed with which the flows collide. We note (a) that the fragments are initially flattened objects ($r_{\rm FRAG}/z_{\rm FRAG} \sim v/\sigma \gg 1$); (b) that $m_{\rm FRAG}$ is not simply the standard 3-D Jeans mass evaluated at the post-shock density and velocity dispersion – it is larger by a factor $(v/\sigma)^{1/2}$; and (c) that our analysis ignores magnetic fields and the possibility that the post-shock gas is turbulent. If present, both magnetic fields and turbulence will act to increase the minimum fragment mass.

2-D one-shot fragmentation has the advantage that the fastest-condensing fragment has finite size, i.e. fragments with initial radius $\sim r_{\rm FRAG}$ condense out faster than either larger or smaller fragments. Moreover, we can analyse the growth of a fragment in a shock-compressed layer, taking account of the continuing inflow of matter into the fragment. Hence we can identify the smallest fragment which can cool radiatively fast enough to dispose of *both* the PdV work being done by compression, *and* the energy being dissipated at the accretion shock where matter continues to flow into the fragment; these two sources of heat turn out to be comparable. We find (Boyd & Whitworth, 2005) that for shocked gas with temperature $T \sim 10\,{\rm K}$ and no turbulence (i.e. velocity dispersion, σ, equal to the isothermal sound speed, $0.2\,{\rm km\,s^{-1}}$), the smallest fragment which can condense out is less than $0.003\,{\rm M}_{\odot}$, and fragments with mass below $0.005\,{\rm M}_{\odot}$ condense out for a wide range of pre-shock density ρ and shock-speed v (as illustrated on Fig. 1). We emphasise that this analysis is more robust than the standard one based on 3-D hierarchical fragmentation, on two counts. (i) The fragments have condensation timescales shorter than all competing length scales (a well known property of layer fragmentation, e.g. Larson, 1985), so they do not tend to merge

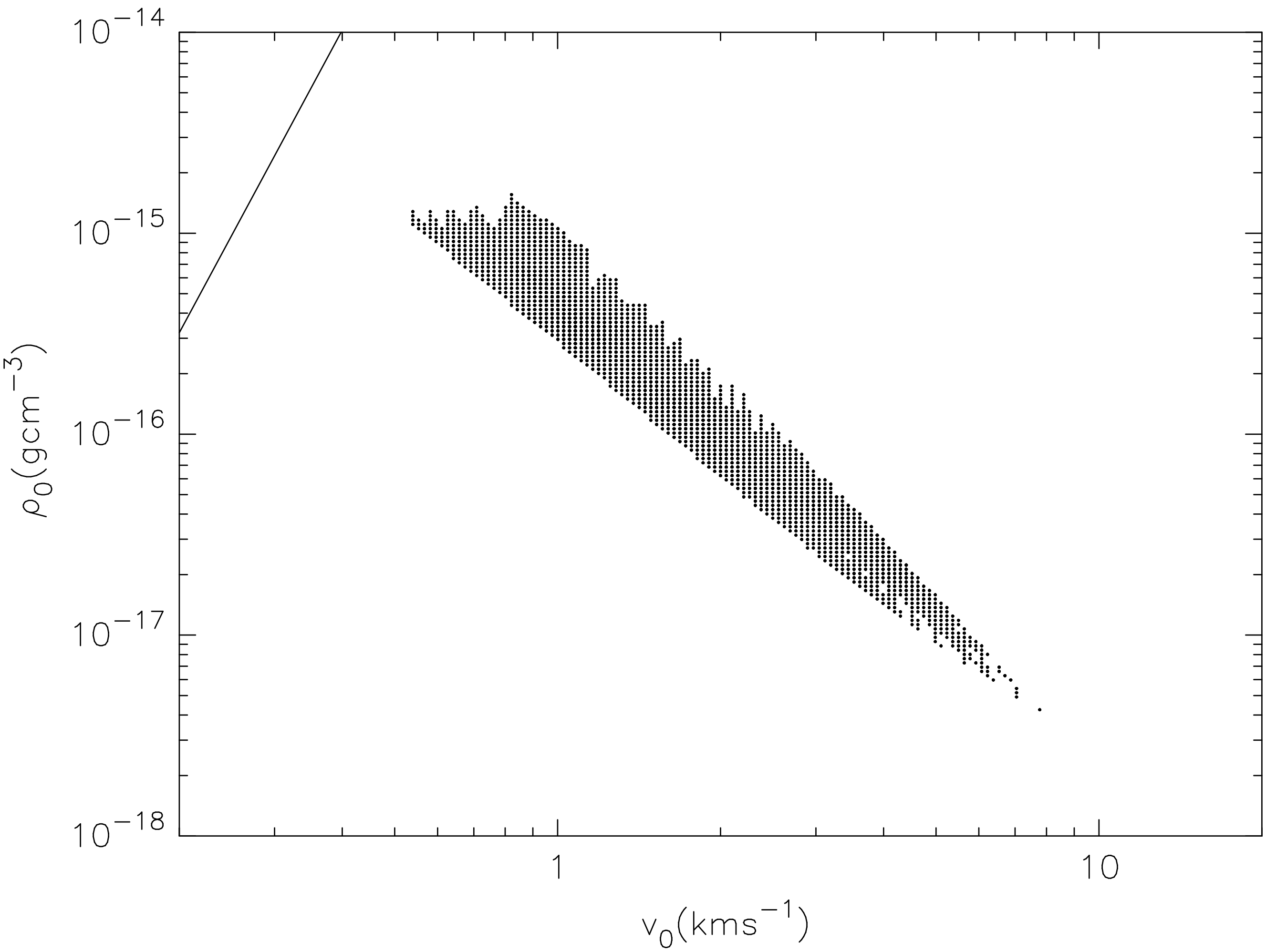

Fig. 1. A log/log plot of the (ρ, v) plane. The dots mark combinations of pre-shock density. ρ, and collision speed, v, for which the fastest growing fragment has a mass less than $0.005\,\mathrm{M}_\odot$; we assume that the effective post-shock sound speed is $\sigma = 0.2\,\mathrm{km\,s}^{-1}$, corresponding to molecular gas at $10\,\mathrm{K}$. The irregularities in the boundaries of this region reflect the tendency of marginally unstable low-mass fragments to undergo pulsations before they collapse. The solid line is the locus below which ρ must fall if our treatment of the radiation from the accretion shock is to be valid; see Boyd & Whitworth (2005) for details.

with their neighbours. (ii) Ongoing accretion is taken into account. Indeed, the smallest fragment of all starts off with mass $0.0011\,\mathrm{M}_\odot$, and grows to $0.0027\,\mathrm{M}_\odot$ before its contraction becomes non-linear. We conclude that stars with masses down to $0.003\,\mathrm{M}_\odot$ can condense out of shock-compressed layers. If the temperature of the post-shock gas can be reduced further still, to below $\sim 6\,\mathrm{K}$, then it is even possible to form 'stars' with masses below $0.001\,\mathrm{M}_\odot$.

4. Formation by disc fragmentation

Another possibility is that an initially massive prestellar core (i.e. significantly more massive than a brown dwarf) spawns brown dwarfs by fragmentation. The fragmentation of collapsing cores is a large and complicated topic. However, one of the main fragmentation mechanisms which operates in numerical simulations is that a relatively massive primary protostar forms, surrounded by a massive disc-like structure (albeit not necessarily a relaxed rotationally supported disc), and then lower-mass secondary protostars – including proto–brown-dwarfs – condense out of the disc (e.g. Bate, Bonnell & Bromm, 2002a,b, 2003; Hennebelle et al., 2004; Goodwin et al. 2004a,b,c). This is the mechanism of core fragmentation on which we shall concentrate here.

If we consider a relaxed massive disc in isolation, there is some doubt as to whether it will fragment gravitationally, spawning low-mass companions to the central primary protostar, or whether spiral modes will act to quickly redistribute angular momentum, thereby stabilising – and ultimately dissipating – the disc before it can fragment. However, if a massive protostellar disc interacts impulsively with another disc, or with a naked star, or if the disc simply never has time to relax towards an equilibrium state, then it can be launched directly into the non-linear regime of gravitational instability, and fragmentation is then much more likely. In the dense proto-cluster environment where most protostars are born, such impulsive interactions must be quite frequent. Therefore Boffin et al. (1998) and Watkins et al. (1998a,b) have simu-

lated parabolic interactions between two protostellar discs, and between a single protostellar disc and a naked protostar. All possible mutual orientations of spin and orbit are sampled. The critical parameter turns out to be the effective shear viscosity in the disc. If the Shakura-Sunyaev parameter is low, $\alpha_{\rm SS} \sim 10^{-3}$, most of the secondary protostars have masses in the range $0.001\,{\rm M}_\odot$ to $0.01\,{\rm M}_\odot$. Conversely, if $\alpha_{\rm SS}$ is larger, $\alpha_{\rm SS} \sim 10^{-2}$, most of the secondary protostars have masses in the range $0.01\,{\rm M}_\odot$ to $0.1\,{\rm M}_\odot$. The formation of low-mass companions is most efficient for interactions in which the orbital and spin angular momenta are all parallel; on average 2.4 low-mass companions are formed per interaction in this case. If the orbital and spin angular momenta are randomly orientated with respect to each other, then on average 1.2 companions are formed per interaction.

In the above simulations the gas is assumed to behave isothermally, which is probably a reasonable assumption, since the discs are large (initial radius $1000\,{\rm AU}$) and most of the secondary protostars form at large distance (periastra $\gtrsim 100\,{\rm AU}$). However, disc fragmentation is probably not possible at smaller radii because the ambient temperature close to the central primary protostar is higher and the surface-density of the disc is also higher. Consequently the optical depths through proto-fragments are higher and they are unable to cool radiatively sufficiently fast to condense out (Rafikov, 2005); instead they contract adiabatically, bounce, and are shredded by tidal forces. Thus gravitational fragmentation is probably limited to the outer parts of such discs. Rice et al. (2003) present SPH simulations of discs fragmentating gravitationally at small radii ($\sim 10\,{\rm AU}$), but they use a phenomenological cooling law of the form $du/dt = -u/t_{\rm COOL}$, and the values of $t_{\rm COOL}$ which they invoke are unrealistically short; also their cooling law seems to admit indefinite cooling and their discs appear to fragment only after the cooling becomes catastrophic. Boss (2001, 2003) also presents simulations of discs fragmentating gravitationally at small radii, performed using a finite difference code with radiation transport. However, the reality of the fragments he finds is questionable on two counts. First, in evaluating the boundedness of the fragments he appears to neglect their internal kinetic energy; in a fragment which is bouncing, or contracting but destined to bounce, this can be a dominant term in the Virial Theorem. Second, he argues that his fragments are cooling by convection, but convection cannot contribute to the cooling of a fragment which is condensing out on a dynamical timescale. The velocity fields which Boss attributes to convective motions may actually be due to bouncing – in which case they will lead to dissolution of his fragments by shredding.

This may help to explain the Brown Dwarf Desert. Brown dwarf companions to solar-type primaries can form by disc fragmentation, but only at large radii. To end up in closer orbits, they must either accrete material with low specific angular momentum, which will tend to increase their mass; or they must interact dynamically with a third star, but this tends to place the more massive star in the close orbit, and to eject the less massive star (i.e. the brown dwarf).

We note that the two mechanisms discussed thus far are not mutually exclusive. If the initial prestellar core is already of very low mass, then it will inevitably produce a low-mass protostar, irrespective of whether it fragments or not. If it has higher mass, it can only produce a very low-mass protostar by fragmenting, and one possible mode of fragmention involves the formation of a disc.

5. Formation by ejection

The collapse of a prestellar core is unlikely to lead to a single star. Even quite modest levels of turbulence (e.g. Goodwin, Whitworth & Ward-Thompson, 2004a) and/or global rotation (Cha & Whitworth, 2003; Hennebelle et al., 2004) are sufficient to ensure fragmentation. Hence prestellar cores usually spawn small-N clusters of protostars ($N \sim 2\,{\rm to}\,6$; e.g. Hubber & Whitworth, 2005), which then grow by competitive accretion and interact dynamically (Whitworth et al., 1995; Bonnell et al., 2001). Protostars which get ejected from the core before they have time to grow to $0.075\,{\rm M}_\odot$ end up as brown dwarfs (Reipurth & Clarke, 2001). It seems inescapable that this mechanism occurs in nature, since all that is required is the formation and coexistence of more than two protostars in a core, with one of them being less massive than $0.075\,{\rm M}_\odot$; N-dody dynamics will then almost inevitably eject one of the protostars, and usually the least massive one.

Several numerical simulations have been performed, using SPH with sink particles, to demonstrate the viability of this mechanism, both in cores with high levels of turbulence (Bate, Bonnell & Bromm, 2002a,b, 2003; Delgado Donate, Clarke & Bate, 2003, 2004), and in cores with low levels of turbulence (Goodwin, Whitworth & Ward-Thompson, 2004a,c). Many of the brown dwarfs formed in these simulations retain low-mass discs ($M_{\rm DISC} \lesssim 0.010\,{\rm M}_\odot$ and $R_{\rm DISC} \lesssim 40\,{\rm AU}$) even after ejection, from which they continue to accrete. They also have a radial velocity distribution which is scarcely distinguishable from that of the hydrogen-burning stars. This is firstly because part of the overall velocity dispersion is due to the motions of the different cores relative to one another, and this part is inherited by all stars; and secondly because the brown dwarfs are ejected with rather modest velocities ($\lesssim 1\,{\rm km\,s^{-1}}$), and the higher-mass stars involved in the ejection also have increased velocity dispersion due to their recoil and their now being in a harder binary system. The main concern with these simulations is that, by invoking sink particles, protostellar embryos are instantaneously converted into point masses. This predisposes them to dynamical ejection, and prohibits them from merging or fragmenting further. Therefore the efficiency of the mechanism may have been overestimated.

Additional support for the mechanism comes from Goodwin et al. (2004b), who present an ensemble of simulations of the collapse and fragmentation of cores having a mass spectrum, density profiles, and low levels of turbulence, matched to those observed in Taurus. These simulations reproduce rather well the unusual stellar IMF observed in Taurus, in-

cluding the relative paucity of brown dwarfs. As far as we are aware, these are the first simulations to demonstrate a direct causal link between the core mass spectrum and the stellar IMF.

Again we note that this mechanism does not exclude the previous two; indeed it requires formation by fragmentation of a collpasing core as a precursor to produce the low-mass protostellar embryos which then get ejected. However, ejection is unlikely to be the only mechanism forming brown dwarfs, since it seems very unlikely to produce the rather large numbers of close BD-BD binaries observed.

6. Formation by photo-erosion

A fourth – and somewhat separate – mechanism for forming brown dwarfs is to start with a pre-existing core of standard mass (i.e. $\gtrsim \mathrm{M}_\odot$)and have it overrun by an HII region (Hester et al., 1996). As a result, an ionisation front (IF) starts to eat into the core, 'photo-eroding' it. The IF is preceded by a compression wave (CW), and when the CW reaches the centre, a protostar is created, which then grows by accretion. At the same time, an expansion wave (EW) is reflected and propagates outwards, setting up the inflow which feeds accretion onto the central protostar. The outward propagating EW soon meets the inward propagating IF, and shortly thereafter the IF finds itself ionising gas which is so tightly bound to the protostar that it cannot be unbound by the act of ionisation. All the material interior to the IF at this juncture ends up in the protostar. On the basis of a simple semi-analytic treatment, Whitworth & Zinnecker (2004) show that the final mass is given by

$$M \;\sim\; 0.01\,\mathrm{M}_\odot\;\left(\frac{a_{\mathrm{I}}}{0.3\,\mathrm{km\,s^{-1}}}\right)^{6}\;\left(\frac{\dot{\mathcal{N}}_{\mathrm{LyC}}}{10^{50}\,\mathrm{s^{-1}}}\right)^{-1/3} \times\;\left(\frac{n_{\mathrm{O}}}{10^{3}\,\mathrm{cm^{-3}}}\right)^{-1/3}\,, \quad (5)$$

where a_{I} is the isothermal sound speed in the neutral gas of the core, $\dot{\mathcal{N}}_{\mathrm{LyC}}$ is the rate at which the star(s) exciting the HII region emit hydrogen-ionising photons, and n_{O} is the density in the ambient HII region.

This mechanism is rather robust, in the sense that it produces very low-mass stars for a wide range of initial conditions, and these conditions are likely to be realized in nature. Indeed, the evaporating gaseous globules (EGGs) identified in M16 by Hester et al. (1996) – and subsequently in other HII regions – would appear to be pre-existing cores being photo-eroded in the manner we have described. However, the mechanism is also very inefficient, in the sense that it usually takes a rather massive pre-existing prestellar core to form a single very low-mass star. Moreover, the mechanism can only work in the immediate vicinity of an OB star, so it cannot explain the formation of all brown dwarfs, and another mechanism is required to explain those seen in star formation regions like Taurus. Brown dwarfs formed in this way should include close BD-BD binaries, but they are unlikely to retain large accretion discs.

7. Conclusions

We have discussed four possible mechanisms for forming brown dwarfs: turbulent fragmentation, disc fragmentation, dynamical ejection and photo-erosion. None of these is mutually exclusive, and in fact the first three may occur consecutively. We emphasise that none of these mechanisms has been modelled properly with a fully radiative 3-D magneto-hydrodynamical code. Therefore, neither the thermal effects which presumably determine the minimum mass for star formation, nor the angular momentum transport processes which presumably determine the binary statistics, nor the N-body dynamics which presumably determine the clustering properties of brown dwarfs, has yet been properly evaluated.

References

Bate MR, Bonnell IA, Bromm V, 2002a, MNRAS, 332, L65
Bate MR, Bonnell IA, Bromm V, 2002b, MNRAS, 336, 705
Bate MR, Bonnell IA, Bromm V, 2003, MNRAS, 339, 577
Boffin HMJ, Watkins SJ, Bhattal AS, Francis N, Whitworth AP, 1998, MNRAS, 300, 1189
Boss AP, 2001, ApJ, 563, 367
Boss AP, 2003, ApJ, 610, 456
Bonnell IA, Clarke CJ, Bate MR, Pringle JE, 2001, MNRAS, 324, 573
Boyd DFA, Whitworth AP, 2004, A&A, 430, 1059
Cha S-H, Whitworth AP, 2003, MNRAS, 340, 91
Delgado Donate EJ, Clarke CJ, Bate MR, 2003, MNRAS, 342, 926
Delgado Donate EJ, Clarke CJ, Bate MR, 2004, MNRAS, 347, 759
Elmegreen BG, 2000, ApJ, 530, 277
Goodwin SP, Whitworth AP, Ward-Thompson D, 2004a, A&A, 414, 633
Goodwin SP, Whitworth AP, Ward-Thompson D, 2004b, A&A, 419, 543
Goodwin SP, Whitworth AP, Ward-Thompson D, 2004c, A&A, 423, 169
Hayashi C, Nakano T, 1963, Prog. Theor. Phys., 30, 460
Hennebelle P, Whitworth AP, Cha S-H, Goodwin SP, 2004, MNRAS, 348, 687
Hester JJ, et al., 1996, AJ, 111, 2349
Hoyle F, 1953, ApJ, 118, 513
Hubber DA, Whitworth AP, 2005, A&A, 437, 113
Kumar SS, 1963, ApJ, 137, 1121
Larson RB, 1985, MNRAS, 214, 379
Low C, Lynden-Bell D, 1976, MNRAS, 176, 367
Masunaga, Inutsuka S, 1999, ApJ, 510, 822
Motte F, André Ph, Neri R, 1998, A&A, 336, 150
Nakajima T, Oppenheimer BR, Kulkarni SR, et al., 1995, Nature, 378, 463
Oppenheimer BR, Kulkarni SR, Matthews K, Nakajima T, 1995, Science, 270, 1478
Padoan P, Nordlund Å, 2002, ApJ, 576, 870
Rafikov RR, 2005, ApJ,
Rebolo R, Zapatero Osorio MR, Martín EL, 1995, Nature, 377, 129
Rees MJ, 1976, MNRAS, 176, 483
Reipurth B, Clarke CJ, 2001, AJ, 122, 432
Rice WKM, Armitage PJ, Bate MR, Bonnell IA, 2003, MNRAS, 339, 1025
Silk JI, 1977, ApJ, 214, 152
Watkins SJ, Bhattal AS, Boffin HMJ, Francis N, Whitworth AP, 1998a, MNRAS, 300, 1205
Watkins SJ, Bhattal AS, Boffin HMJ, Francis N, Whitworth AP, 1998b, MNRAS, 300, 1214

Whitworth AP, Chapman SJ, Bhattal AS, Disny MJ, Pongracic H, Turner JA, 1995, MNRAS, 277, 727
Whitworth AP, Zinnecker H, 2004, A&A, 427, 299